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Orogenic and Glacial Research in Pristine Southern Alaska

Southern Alaska is an exceptional natural laboratory for studying a range of geologic problems, including the links between orogenic processes, landscape modification by glacial processes, and continental margin sedimentation. Geologic processes operate at rapid rates along the southern Alaskan margin, which allows scientists to concurrently collect data on tectonic deformation, uplift, erosion, and sedimentation, and develop comprehensive models that connect these diverse processes. Significant advancements have been made in studying fundamental geologic processes in this region. However, efforts to link these into comprehensive models are in their infancy and fundamental research questions remain. The National Science Foundation's MARGINS Source-to-Sink program (see http://www.ldeo.columbia.edu/margins/SciencePlan.15Nov.pdf) will provide an interdisciplinary group of geoscientists the opportunity to merge these studies and significantly advance our understanding of continental margins.

The intention of the Source-to-Sink program is to encourage diverse scientists, including those not presently working in the chosen focus and allied sites, to submit proposals to work in those areas. To help accomplish that goal, this and other articles to follow will describe the current state of knowledge about these sites and pose questions that merit further research, both within the context of MARGINS and other geoscience programs.

Southern Alaska, including the south-central and southeastern regions (Figure 1), is one of the premier locations on Earth where tectonically-driven orogenic processes, glacial and other surficial processes, and continental margin sedimentation can be studied in unison, allowing the development of quantitative models that link this broad suite of processes. This setting features high mountains next to the ocean, extremely high sediment yields, essentially no intervening basins to trap sediment, active faults beneath mountains and mountain glaciers, and a location where the orogeny coincides with extensive glacial cover. In this continental margin setting, erosion reduces the mean height of the continental edge, while the transport and deposition of eroded material to the Pacific builds a wide continental margin.

Over recent years, a number of thought-provoking studies have explored the connections between orogenic processes, surficial processes and climate [e.g., *Raymo and Ruddiman*, 1992; *Molnar and England*, 1990]. Chemical weathering and rapid sequestration of eroded material may also play a role in altering the climate by affecting the global CO_2 budget. Theoretical considerations and field studies strongly suggest that erosion rates and rock uplift rates are often closely matched in diverse settings. This is unlikely to be fortuitous; it more likely reflects direct, but as yet poorly understood linkages between geodynamic and surficial processes. Patterns and rates of erosion may strongly influence the evolution of orogenic belts and vice versa. Finally, as climate includes patterns of precipitation, it controls both glacial dynamics and erosion; margin strata are therefore likely to contain a strong climatic signal ranging from the seasonal to glacial-interglacial scale. Within this complex geological system, glacial and periglacial erosion play multiple roles of direct interest to the MARGINS program. For this reason, southern Alaska was chosen for allied field studies within the MARGINS Source-to-Sink program. The goal of Source-to-Sink is to discern the relationships among processes relevant to sediment production, transport, accumulation, and preservation on margins at multiple temporal and spatial scales, from turbulence to tectonics and from sedimentary fabric to sequence stratigraphy and basin analysis. The purpose of an allied field study is to document source-to-sink processes relevant to the continental margin primary focus sites—New Guinea and New Zealand—that cannot be effectively studied at those sites. Southern Alaska was chosen by the MARGINS community for field studies of glacial sediment production, transport, and accumulation.

This research will complement the longer-term examination of the dispersal systems along the South Island of New Zealand and provide valuable insights into the processes of sediment production and transport that would have been more globally widespread during glacial periods. The massive valley glaciers in southern Alaska are the largest in the world and they have many attributes, such as size, dynamics, and sediment production in common with those of the Late Glacial Maximum (LGM) valley glaciers. Moreover, massive piedmont lobes in the area (for example, Malaspina and Bering Glaciers, Figure 1) represent perhaps the closest modern analogs to the temperate portions of the Laurentide and Fennoscandian ice sheets during the Quaternary.

Tectonic and Orogenic Processes in Southern Alaska

The primary features of the present-day orogen evolved during the last 25 Ma when the Yakutat block (Figure 2) first detached from the margin as a strike-slip sliver that was transported northward along the Queen Charlotte transform fault and then collided beginning at 25

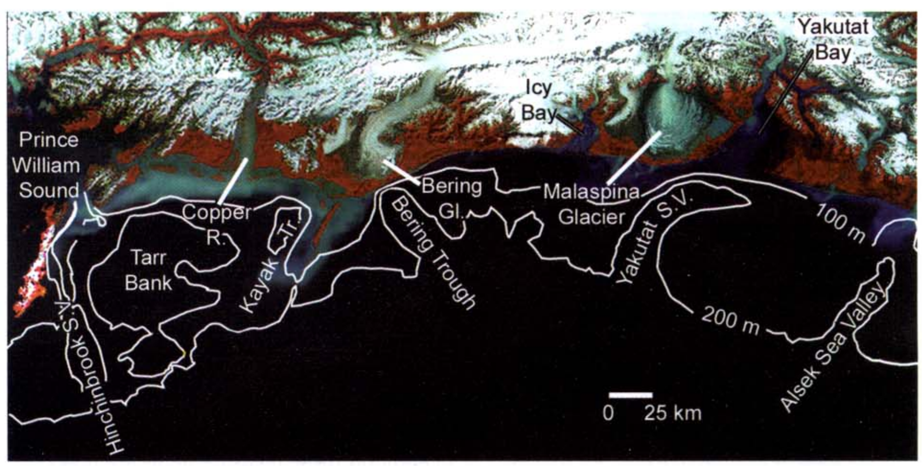

Fig. 1. False color composite Landsat photomosaic of southern Alaska from August 1973. Convergence of the Pacific and North American Plates has created the Chugach-St. Elias Range with peaks exceeding 5 km in elevation. The coastal mountains trap precipitation, creating glacial conditions that have existed along this coastline since the late Miocene. Currently, large piedmont glaciers—Bering and Malaspina—and dozens of alpine and tidewater glaciers originate from the high mountains.

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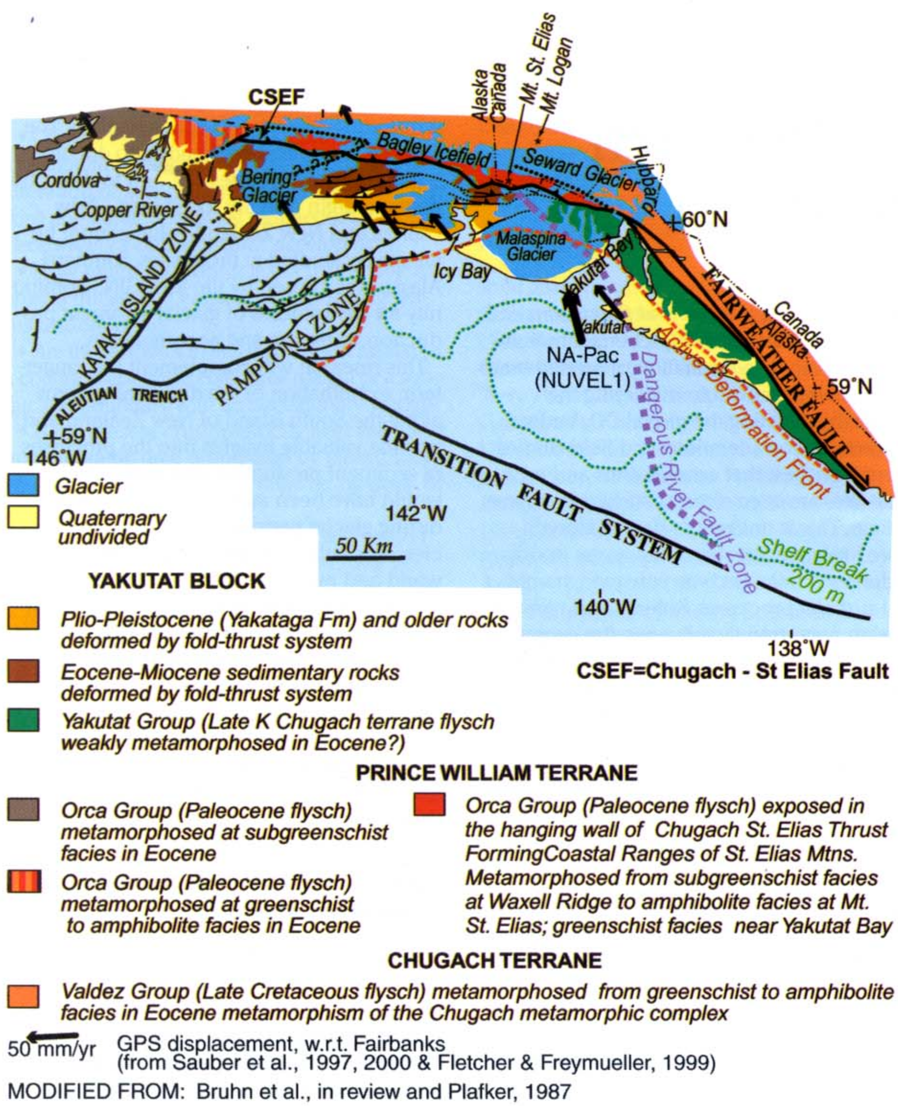

Fig. 2. Tectonic map of the Gulf of Alaska region showing major rock units and structures within the orogen, as well as their relationships to the major ice masses. Figure is after Plafker [1987].

Ma with the eastern end of the Aleutian trench [e.g., *Plafker et al.*, 1994]. This sliver was dragged into the syntaxis via a small subducting slab that generated the Wrangell volcanic field (Figure 2), a short, but extremely active, magmatic arc segment that is offset ~500 km from the main Alaskan-Aleutian arc. Contraction of this sliver has constructed the Fairweather-St. Elias orogen. It has the highest coastal relief on Earth; Mt. St. Elias rises from the sea to ~5800 m over a distance of ~18 km. The extreme relief but relatively low mean elevation of the coastal mountain range, varying from 2500 m to 1100 m from east to west, reflects the variety of processes acting on this orogen, including extremely rapid erosion [*Meigs and Sauber*, 2000]. A systematic increase in the width of the orogen from east to west is correlated with an increase in the width of a shallowly dipping segment of the lower plate, a divergence of major upper plate structures, and a decrease in the obliquity of Pacific plate motion relative to interior Alaska. Active offshore deformation within the orogen [*Plafker et al.*, 1994] appears to be concentrated in two distinct northeast-trending, fold-thrust belts—the Kayak and Pamplona zones—that project onshore to the positions of the two largest glaciers in the system, the Bering-Bagley and Seward-Malaspina systems, respectively. These glaciers also correspond to the boundaries of three distinct structural domains on land, suggesting that they cover active structures. Geodetic measurements give precise estimates of ongoing strain accumulation and provide insight into the dynamics of the subduction zone and coastal mountains. In addition, these measurements are now one of the primary tools for assessing the seismic potential of a given region. Locally, the regional tectonic feature that seems to have the greatest geodetic influence is a locked plate interface at depths less than 40 km. Short-term horizontal displacement rates are ~4 cm y^{-1} at coastal sites and less than 2 cm y^{-1} above the down-dip portion of the locked zone (Figure 2). The uplift rates estimated from geodetic data reflect tectonic uplift, as well as glacial rebound associated with retreat of the coastal glaciers over the last 100+ years. In lower Glacier Bay, apparent uplift due to rebound occurs at ~4 cm y^{-1}. Short-term strain will be relieved primarily as plate interface earthquakes or as earthquakes on faults within the overriding plate that result in crustal shortening. Many great earthquakes have occurred over the past century between the Alaska Panhandle and Prince William Sound. Five earthquakes of magnitude (M_s) 7.0 or greater have occurred in this region since 1979, and in 1964, the Prince William Sound earthquake (M_w 9.2) resulted in vertical ground displacements of up to 10 m and powerful tsunamis. Strong ground-shaking during the 1964 earthquake lasted several minutes and caused debris flows, landslides, glacial, lake level, and stream discharge fluctuations over much of southern Alaska. Re-sedimentation processes caused by earthquakes can result in rapid sediment transport and deposition and thereby affect the sedimentary record. Glacial processes and seismicity could be linked along the Alaskan margin. During the 1993–1995 Bering Glacier surges, background seismicity increased in the surge source region, where ice thickness decreased by more than 50 m. Also, it is speculated that the initial retreat of the Guyot Glacier in 1899 may have triggered the Yakataga earthquake of that same year, and that further recession of glaciers in Icy Bay led to the 1979 earthquake.

Glacial Processes in Southern Alaska

The warm-based glaciers of southern Alaska are fueled by very high annual snowfall and move at rates of up to hundreds of meters per year. Surging glaciers move 100 m per day or more, but they subsequently undergo rapid retreat. Many of the large glaciers have undergone tens of kilometers of advance and retreat from the coastal mountains onto the continental shelf during the Quaternary, and most Alaskan glaciers advanced significantly during the Little Ice Age. On a longer time scale, the Yakataga formation (up to 5 km in thickness), the glacimarine cover of the Yakutat terrane in this region [*Lagoe et al.*, 1993], records the presence of calving glaciers and abundant sediment delivery to the Alaskan foredeep beginning between 5 Ma and 7 Ma. Tidewater and valley glaciers are found in southern Alaska today. The seasonal delivery of sediment and its annual variations are well documented by ongoing, long-term studies at Matanuska Glacier and can be deduced from sedimentary records in coastal fjords; for example, Prince William Sound and Glacier, Yakutat, and Icy Bays. Moreover, examples of glacial outburst floods (jökulhlaups), which debouch large volumes of sediment and water, have recently occurred and are recorded in both terrestrial and marine deposits. Two such floods received recent study at Alsek River and Kennicott Glacier. These catastrophic flooding events are brief, but they may recur over decades to centuries and can significantly impact downstream sediment storage and accumulation.

Landscape Denudation and the Neogene Sedimentary Record

Worldwide, sediment yields—as a measure of erosion rate—from glaciated basins exceed those for glacier-free basins of comparable size, and sediment yields from the coastal mountains of southern Alaska appear to be the highest in the world [*Hallet et al.*, 1996]. In a recent review of river-suspended sediment loads, southern Alaska has fluvial sediment yields of 10^4 t km^{-2} y^{-1}, quantities similar to rivers of comparable size in southeast Asia and Oceania that have been greatly influenced by anthropogenic activity (Figure 3). In contrast, sediment yields from many tidewater and terrestrial glaciers in southern Alaska currently exceed 10^5 t km^{-2} y^{-1}. Coastal mountains are being cut down by ice as fast as the crustal belt grows. The extreme erosion rates are due in part to high physical weathering rates of diverse rock types heavily affected by metasomatism. Moreover, processes in recently deglaciated terrain, ranging from the frost-induced motion of individual rock fragments to large-scale mass movements, actively transport material downslope into streams draining into fjords and the coast. Glacial erosion also shapes sedimentary basins by overdeepening them, eroding cross-shelf troughs, remobilizing sediments, and influencing isostatic movements. Finally, the impact of high erosion rates on chemical weathering fluxes and on organic carbon burial on the shelf are important open questions that link source-to-sink to geochemical and climate change issues. While most coastlines around the world are experiencing retreat due to rising sea level, coastal plains in southern Alaska are undergoing rapid progradation, periodically and locally greater than 5 km ky^{-1}. Modern sediment accumulation rates in the fjords of southern Alaska are unsurpassed worldwide, exceeding several m y^{-1} and locally can exceed 80 m y^{-1} at glacier termini. Fjords act as sediment traps; they provide a unique method for analyzing Holocene sediment flux because for many glacier systems here, there is minimal sequestration of materials on land before they enter fjord waters. The Holocene terrestrial record of glacial activity is well preserved in the Glacier Bay region, where current studies suggest that a complete record of glacial cycles and sediments and interstadial paleoclimates may exist for the entire Holocene. Such data allow interpretation of the glacial and interglacial signals within the extremely thick sedimentary sequences deposited on the continental shelf of southern Alaska. Here, as much as 350 m of sediment accumulated during the Holocene. On land, substantial outwash plains and glaciolacustrine deposits in the Copper and Alsek drainage basins may also contain a rich but unexplored Holocene history of terrestrial weathering and erosion essential to interpreting the marine record. Thick Copper River deltaic strata may be equally important to defining hydrologic signals. An obvious physical record of weathering and erosion from any mountain range is found in clastic sedimentary sequences produced by sediment delivery to continental margins. Yet, for certain drainage basins where significant quantities of sediment are trapped in foreland basins or flood-plain deposits, the sediment flux carried by a river to the sea—which is the most easily quantifiable measure of denudation of orogenic belts—underestimates the total sediment yield. This significant difficulty does not arise, however, in mountain ranges that are close to the sea as they are in southern Alaska, where terrestrial storage is minimized and foredeep basins are absent.

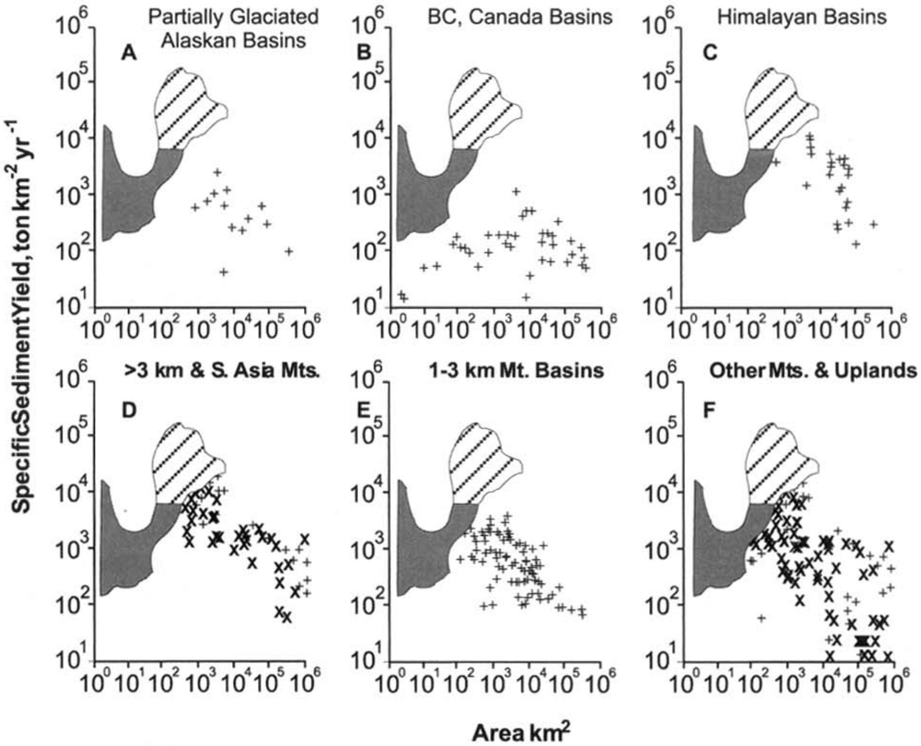

Fig. 3. Sediment yields from glacially dominant basins versus fluvial dominant basins. Glacial basins are shown by the shaded pattern in the upper left quadrant of each figure; Alaskan basins are within the hatched region. Glacial basins are distinct and essentially do not overlap with those of all other major groups of basins: (A) Partially glaciated basins in Alaska; (B) British Columbia; (C) Himalayas. Glacial yields are also distinct from yields from a worldwide set of basins (D, E, F). Figure is after Hallet et al. [1996].

Unanswered Questions

Although glacial, sedimentary, and tectonic processes in southern Alaska have been well studied over the past 25 years, significant questions remain to be answered both within the MARGINS Source-to-Sink initiative and by more general geoscience programs:

Interactions between tectonic and surficial processes

- What is the relationship between heavy precipitation, high erosional and depositional rates, and dynamic tectonic processes? How do these components vary spatially?
- What are long-term versus transient deformation rates on land, and how do you determine them in a system where denudation rates are so high that Quaternary sediments are eroded, along with the structural record of Quaternary faulting?
- Does rapid erosion localize faulting or do areas of localized thrust and transpressional faulting localize glacial erosion?
- What role did the massive input of sediment from land play in constructing the wide continental shelf, and does this influence current localization of faulting?
- What role do glacial advances and retreats play in modulating the occurrence of earthquakes?

Surficial and marine processes

- Present-day sediment delivery rates by large tidewater and terrestrial glaciers are high (~10 mm y^{-1} or higher), but such rates are not sustainable in the long term (uplift rates are a few mm y^{-1}). What are long-term rates of erosion? Do current sediment yields based on fjord sediment accumulation rates tend to overestimate these rates?
- What processes lead to rapid erosion in the region? What are the roles of glacier dynamics and bedrock lithology and structure?
- What is the chemical dimension of rapid glacial erosion, and what might it teach us about variations in chemical input (e.g., Si, Sr, Os, Ge) from the continent to the oceans through glacial/interglacial cycles?
- What can be learned about seasonal and longer-term climate change, tectonics, and glacial erosion rates from the thick shelf and fjord deposits?
- Climate is the first order control on glacial fluctuations, but sediment flux may also significantly affect the advance/retreat of tidewater

and terrestrial glaciers. How do glaciers influence their own stability, and does the sediment record contain a combination of autocyclic and allocyclic sequences?

• Can the Holocene glacial record, including interglacial paleoclimate data and resulting alteration of surficial process, be linked to the fjord and continental shelf sedimentary record?

Geodynamics and structural development

• How much rock uplift is occurring due to crustal thickening caused by shortening versus underplating?

• Are the tectonics in this region most similar to a continent-continent collisional margin or a subduction boundary with an accretionary wedge?

• Is the present crustal velocity field estimated from geodetic data dominated by elastic strain accumulation that will be relieved by deep or shallow crustal structures?

• Why is the present-day orogen segmented into distinct structural domains, and why do these domains appear to move differently than direct North American-Pacific convergence would imply?

• What is the deep structure of the orogen? For example, contractional bends appear to be anomalously large in the southern Alaskan orogen.

• What is the current tsunamigenic potential of the study region?

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